POROUS SURFACES FOR DROPLET ACTUATION AND MOBILITY MANIPULATION USING BACKPRESSURE

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SUMMARY

In this study we explore the underlying mechanisms of droplet actuation and mobility manipulation, when backpressure is applied through a porous medium under a sessile pinned droplet. Momentum conservation and continuity equations along with the Cahn-Hilliard phase-field equations in a 2D computational domain are used to shed light on the on the droplet actuation and movement mechanisms. The droplet actuation mechanism entails depinning of the receding contact line and movement, by means of a forward wave propagation reaching on the front of the droplet. Eventually, the droplet is skipping forward.

INTRODUCTION

Control over the mobility of droplets on surfaces remains an important part of recent research activity, both for understanding the pertaining wetting principles [1] as well as for practical applications including open, closed and digital microfluidics and related technologies, chemical processes in droplets, engineered self-cleaning surfaces, antiicing coatings, membrane contactors, polymer electrolyte fuel cells, heat exchangers etc.

In this direction a variety of approaches have been proposed towards preparing “active”, or “tunable”, or “adaptive”, or “skating-like” surfaces, namely manipulating the mobility of a droplet or a liquid film, mainly based on the respective wetting transitions.

In this direction we have recently developed a method for droplet actuation and mobility manipulation on porous media [2-7]. Contrary to the droplets levitated by an air cushion exhibiting a frictionless mobility, our method provokes only partial depinning of the solid-liquid interface, which is enough to render the droplet mobile and to incite a downward movement. The main advantages of this include the absence of moving parts and the circumvent of electrical, magnetic, optical, vibrational, and acoustical stimuli on the surface. The heat dissipation may be not only minimized but also finely controlled, e.g. by controlling the temperature of the gas feed. Introduction of foreign particles/molecules in the working liquid/droplet is completely avoided. It may accommodate various liquids, i.e. may work on deionized (DI) water to aqueous solutions, as will be evidenced hereafter, and is amenable for integration on devices for active control. Finally the response time is ultra-low, in the order of some ms, and if appropriate microporous structure is selected, its energy demands are significantly lower compared to the other methods.

In this work we shed light on the underlying working mechanisms of droplet actuation and movement induced by backpressure application through a porous medium. The problem is followed by means of simulations encompassing the momentum conservation and the continuity equations along with the Cahn-Hilliard phase-field equations in a 2D domain [8,9]. The results from the theoretical approach are compared to the experimental observations, thus providing a reasonable understanding of the respective droplet actuation and movement mechanisms [10].

RESULTS

In Figure 1 the sliding angle of water droplets of various volumes are presented vs. the applied backpressure on the porous surface. The sliding angle (α) is defined as the minimum tilt angle at which the droplet moves systematically downwards, at a particular backpressure for each droplet volume.

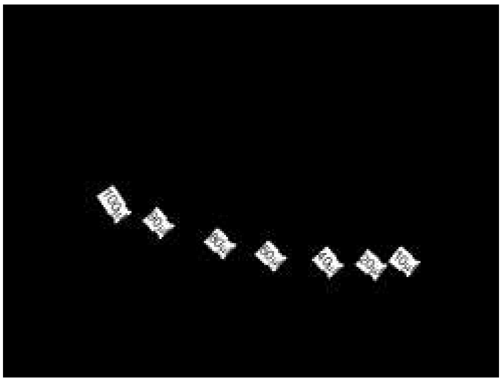

Figure 1. Variation of sliding angle (a) with backpressure. Lines of different DI water droplets volumes are depicted

In Figure 2 we present simulation snapshots that outline a mechanism of droplet movement. The initial conditions of the simulations include a droplet on an inclined porous surface, not necessarily at an equilibrium state, i.e. the initial conditions are only estimations of the expected equilibrium wetting state. For t = 0 s, we enforce a certain rate in which air permeates the substrate (Fa), and furthermore we allow the effect of gravitational forces. Air pockets are gradually formed and expanded (t=0.01 s), some of which coalesce into larger ones (t=0.03 s). The droplet remains pinned until the stretched liquid bridge, formed between the outside air and the air pocket (t=0.08 s) at the rear of the droplet (with respect to the direction of gravity), collapses. The collapse sends a wave forward on the surface of the droplet that reaches the solid surface on the front of the droplet (t=0.086 s to 0.094 s), at which point the droplet gets pinned on the surface (t=0.096 s). Eventually, the droplet has skipped forward by the amount of the solid surface length that gets attached to the front of the droplet.

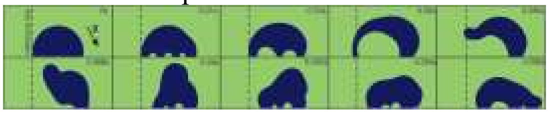

Figure 2. Simulation snapshots of droplet lateral movement on an inclined plane with air permeating the solid substrate.

CONCLUSIONS

We provided insights on the underlying mechanisms of droplet actuation on porous media by means of backpressure and surface inclination; the latter are combined to facilitate active control of droplet mobility. Adjusting the porous backpressure the droplet may be pinned to the surface or may be actuated and move downwards by the presence of a small inclination. The interplay between backpressure and inclination has been quantified for various volumes of DI water and ethanol in DI water droplets. Actuation and mobility control may be realized without a fully developed air cushion under the liquid; therefore Leidenfrost-like dynamics cannot be used. Simulations have shown that the droplet is actuated through a depinning process of the receding contact line and moves by means of forward wave propagation towards the front contact line. The droplet shapes obtained by this numerical approach are fairly compared to the ones observed experimentally, thus providing a reasonable justification of this approach.

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